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On the development of methods and equipment for 2D-tomography in combustion

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Motivation

- **Studying combustion phenomena**

- It is important to know essential combustion parameters such as
  - gas temperature
  - species concentration

      – resolved temporarily and spatially and simultaneously for every point

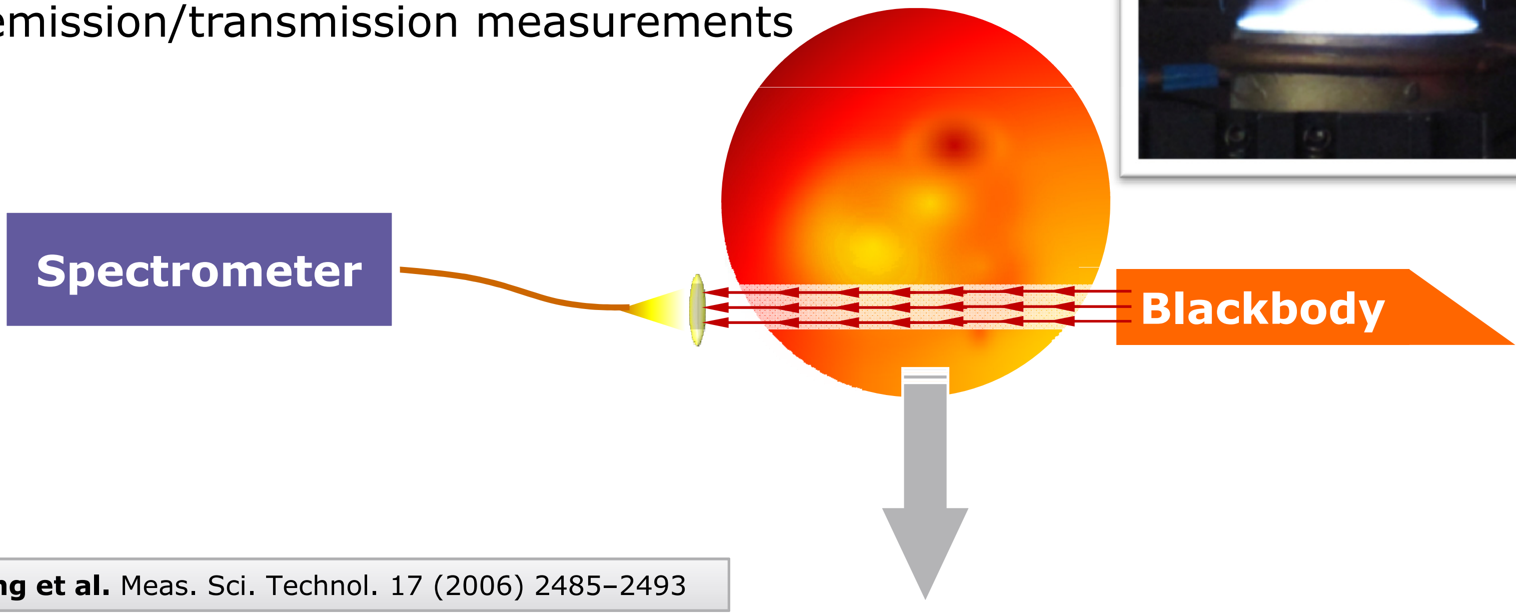
- **Objective of this work**
  - Tomographic reconstruction of
    - gas temperatures
    - species concentrations
  - in flames and hot gas flows

Outline

- **Tomographic reconstruction methods for gas temperatures**
  - development
  - results
- **Equipment suitable for tomographic measurements of gas temperatures**
  - development
  - application
- **Species concentration calculations**
  - theory
  - modeling

Problem Statement

- **Given** is an axisymmetric stable flame produced by a small lab-scale burner*
- The temperature profiles at a number of heights above the burner plate are known*
- **The task** is to reconstruct the temperature profile at a chosen height above the burner
  - from several optical line-of-sight spectral emission/transmission measurements



*__Hartung et al.__ Meas. Sci. Technol. 17 (2006) 2485–2493

Problem Statement: Details

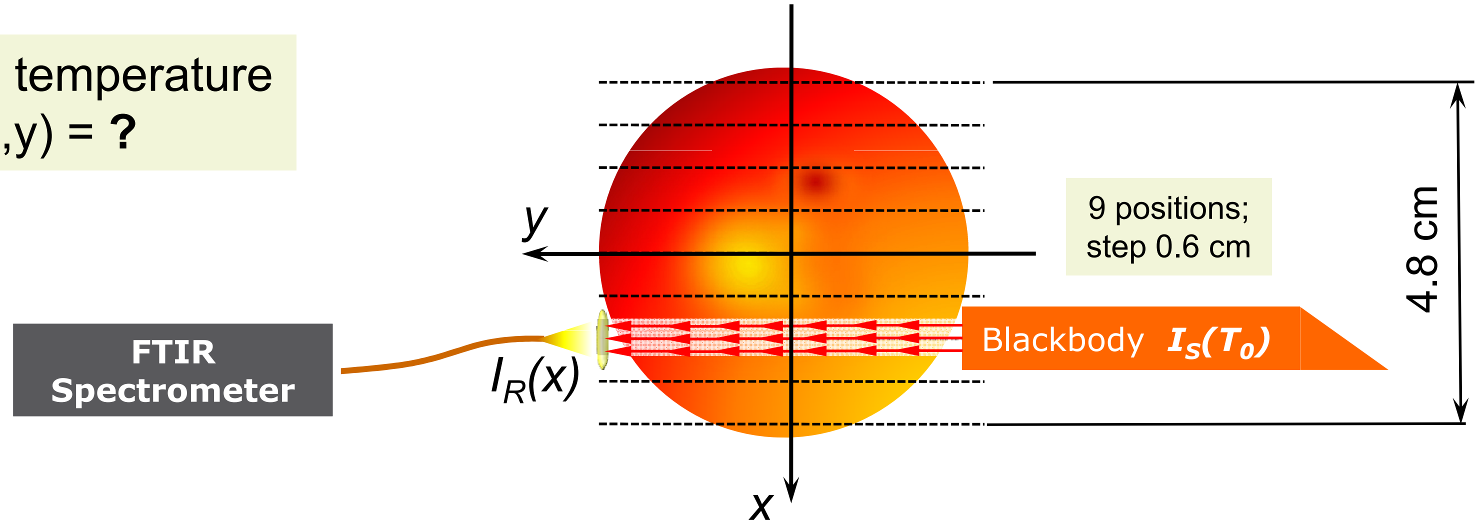
- **Motivation to use optical techniques**
- They are advantageous
  - over thermocouples due to
    - non-intrusiveness
    - high temporal resolution
  - over laser-based techniques due to
    - low cost
    - wide spectral range

- **Motivation to work in the IR spectral range**
  - The major combustion species CO_2 and H_2O have strong fundamental rotational-vibrational bands in the near IR range

- **Equipment used in the experiment**
  - Fourier Transform Infra-Red (FTIR) spectrometer
  - optical fiber
  - optics
  - blackbody radiation source

Parallel Scanning

Gas temperature
$T_g(x,y)$ = **?**



- The spectral irradiance $I(x,y)$ by a beam of monochromatic radiation varies according to*

$$dI(x,y) = \underbrace{-k(T_g)\, I(x,y)\,dy}_{\text{Lambert's Law}} + \underbrace{k(T_g)\, I_{Planck}(T_g)\,dy}_{\text{Kirchhoff's Law}}$$

  - $T_g = T_g(x,y)$ – gas temperature
  - $k(T_g) = k(T_g(x,y))$ – the absorption coefficient
  - $I_{Planck}(T_g)$ – the Planck function at T_g

The monochromatic **radiative transfer equation** without scattering

* **Tourin et al.** Applied Optics 4 (2) (1965) 237–242

Parallel Scanning

- The radiative transfer equation is a **differential equation** with respect to $I(x,y)$
- The solution of it is a complex **integral equation** with respect to $T_g(x,y)$

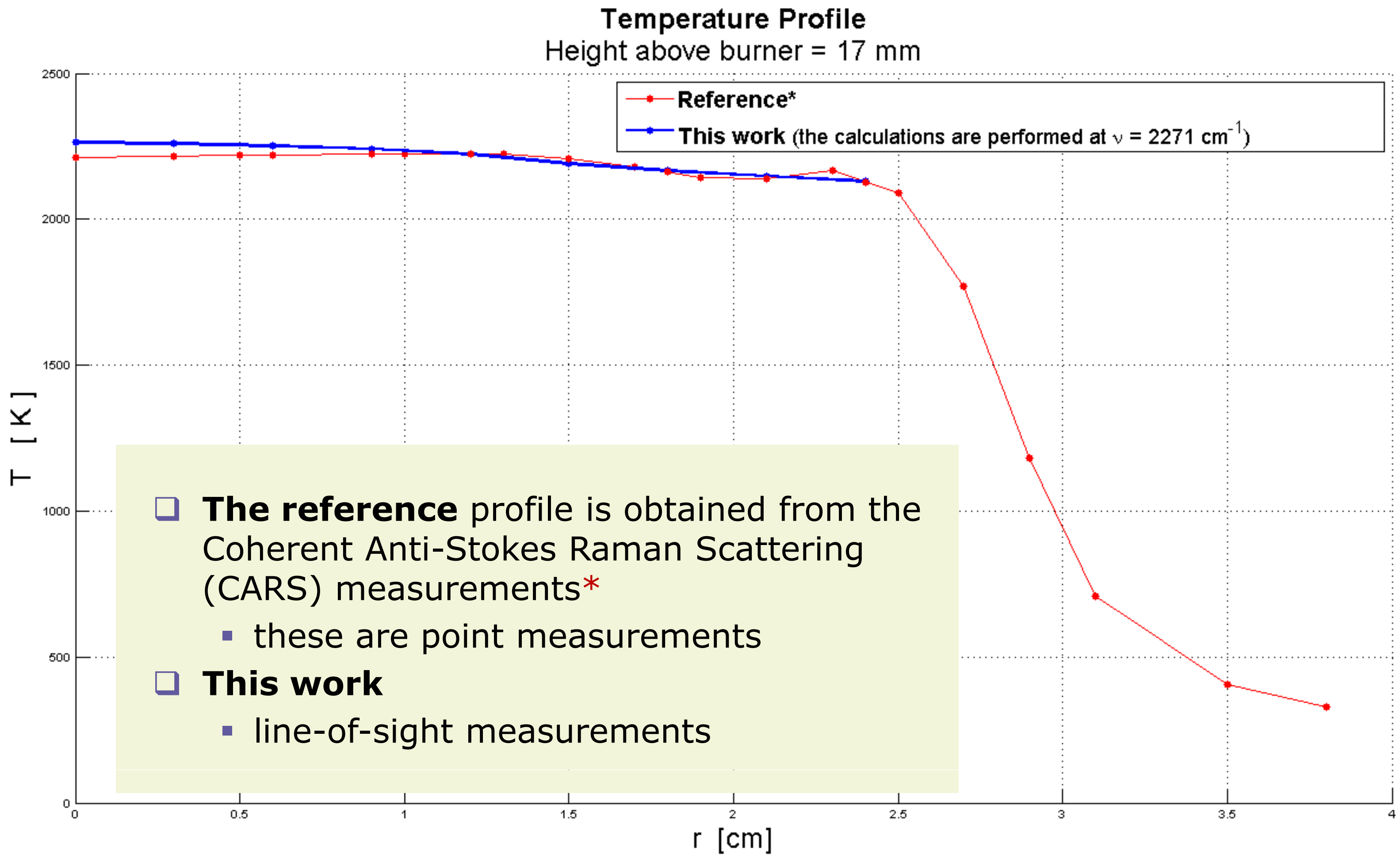
$$\frac{I_R(x)}{I_s(T_0)} = \exp\left(-\int_{y_1(x)}^{y_2(x)} k\big(T_g(x,y)\big)\,dy\right) +$$

$$+\left\{\int_{y_1(x)}^{y_2(x)} k\big(T_g(x,y)\big)\frac{I_{Planck}\big(T_g(x,y)\big)}{I_s(T_0)}\exp\left(\int_{y_1(x)}^{y} k\big(T_g(x,y')\big)\,dy'\right)dy\right\}\times$$

$$\times\exp\left(-\int_{y_1(x)}^{y_2(x)} k\big(T_g(x,y)\big)\,dy\right)$$

- In this work it was solved by means of iterative approximations:
  - in the i th approximation an Abel's integral equation is solved with respect to $k_i(T_{gi}(x,y))$
  - T_{gi}(x,y) is found by means of modeling using the spectroscopic databases
  - These values of k_i and T_{gi} are used in the next approximation

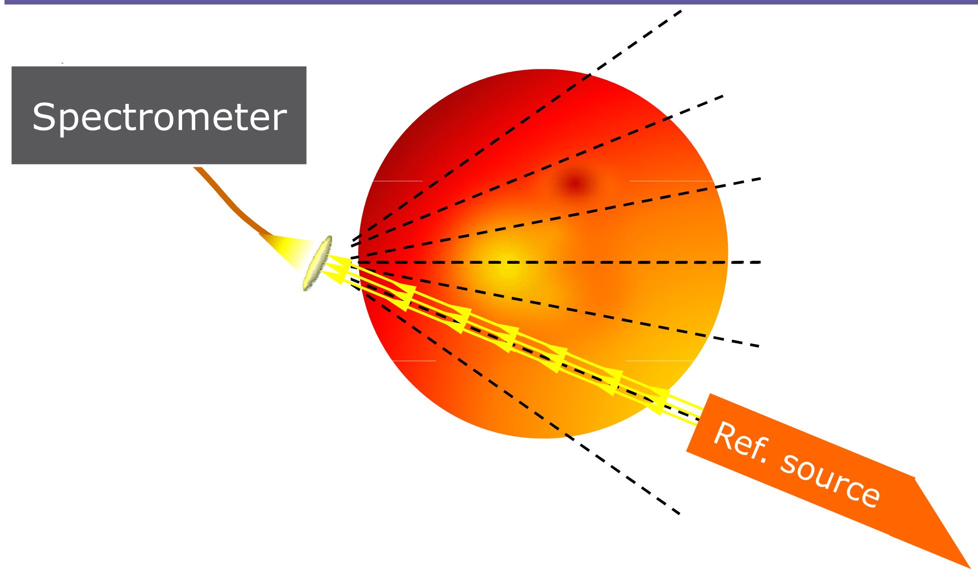
Parallel Scanning

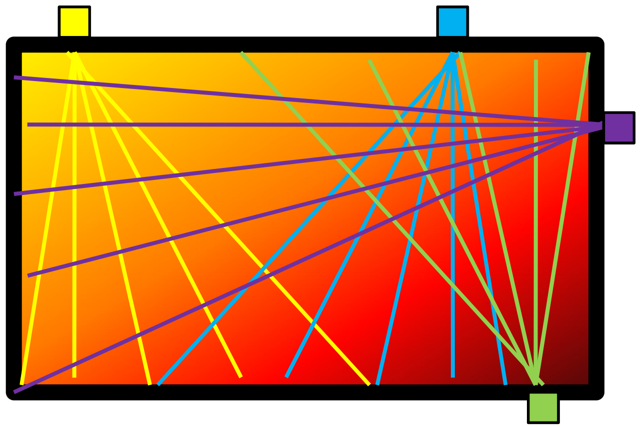


- ❑ **The reference** profile is obtained from the Coherent Anti-Stokes Raman Scattering (CARS) measurements*
  - these are point measurements
- ❑ **This work**
  - line-of-sight measurements

*__Hartung et al.__ Meas. Sci. Technol. 17 (2006) 2485–2493

Sweeping Scanning



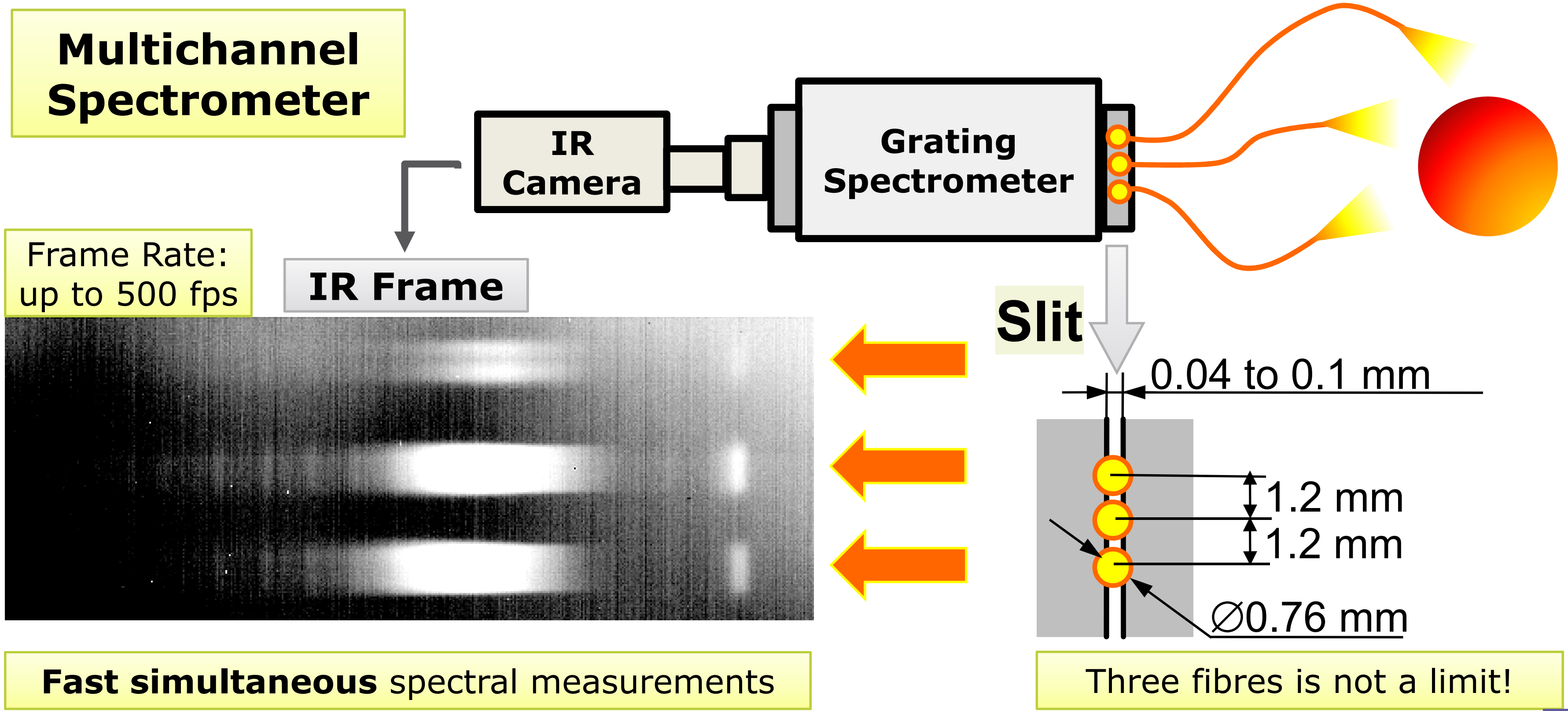


- **Advantage**
  - More practicable with respect to the real conditions of an industrial scale
    - The idea is to use several synchronized spectrometers with the sweeping scanning
    - The walls of a boiler can be used as a reference source

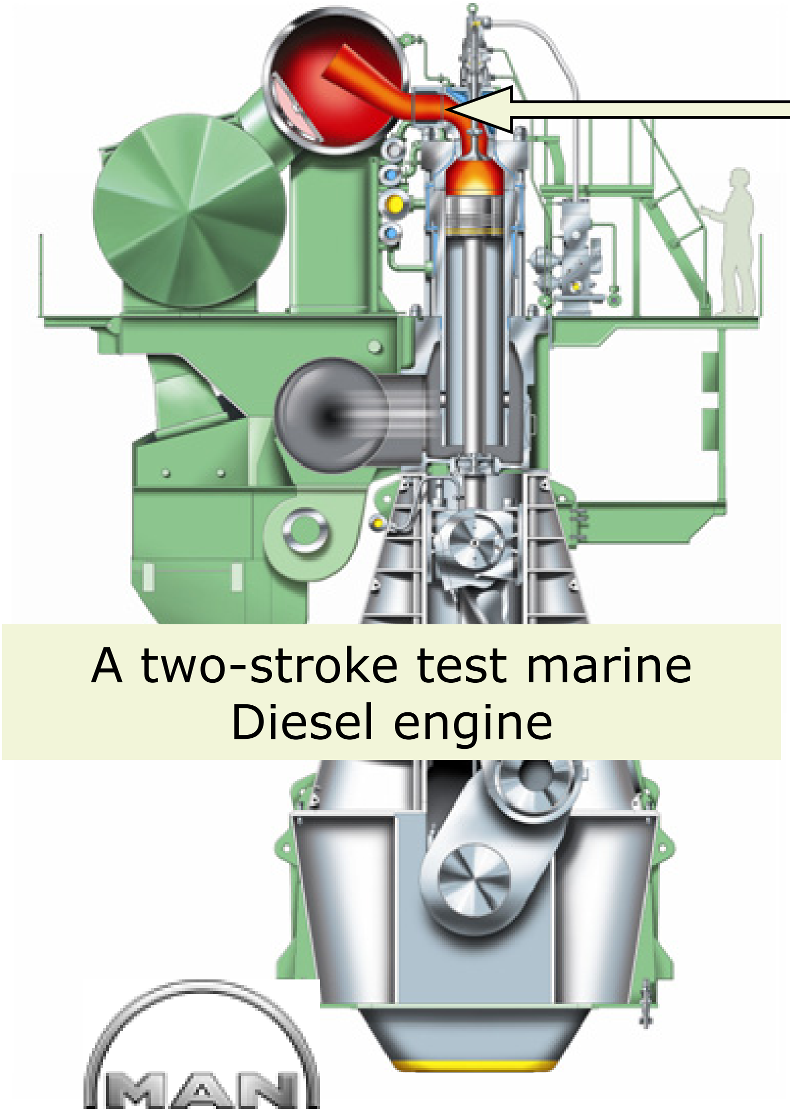
- **Equations**
  - The same as in the parallel case but just converted to polar coordinates

Equipment for Tomography

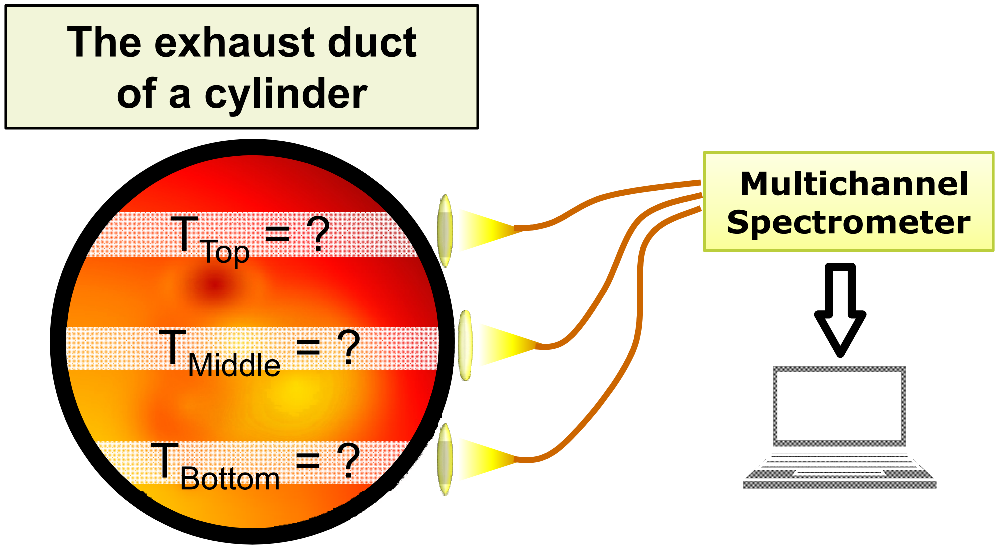
- **Objective**
  - It is essential for tomography to have simultaneous spectral measurements from several lines of sight
- **Approach**
  - Several optical fibers + Grating spectrometer + IR Camera



Multichannel Spectrometer



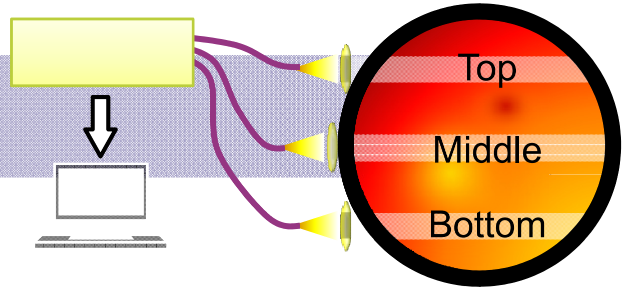
A two-stroke test marine Diesel engine



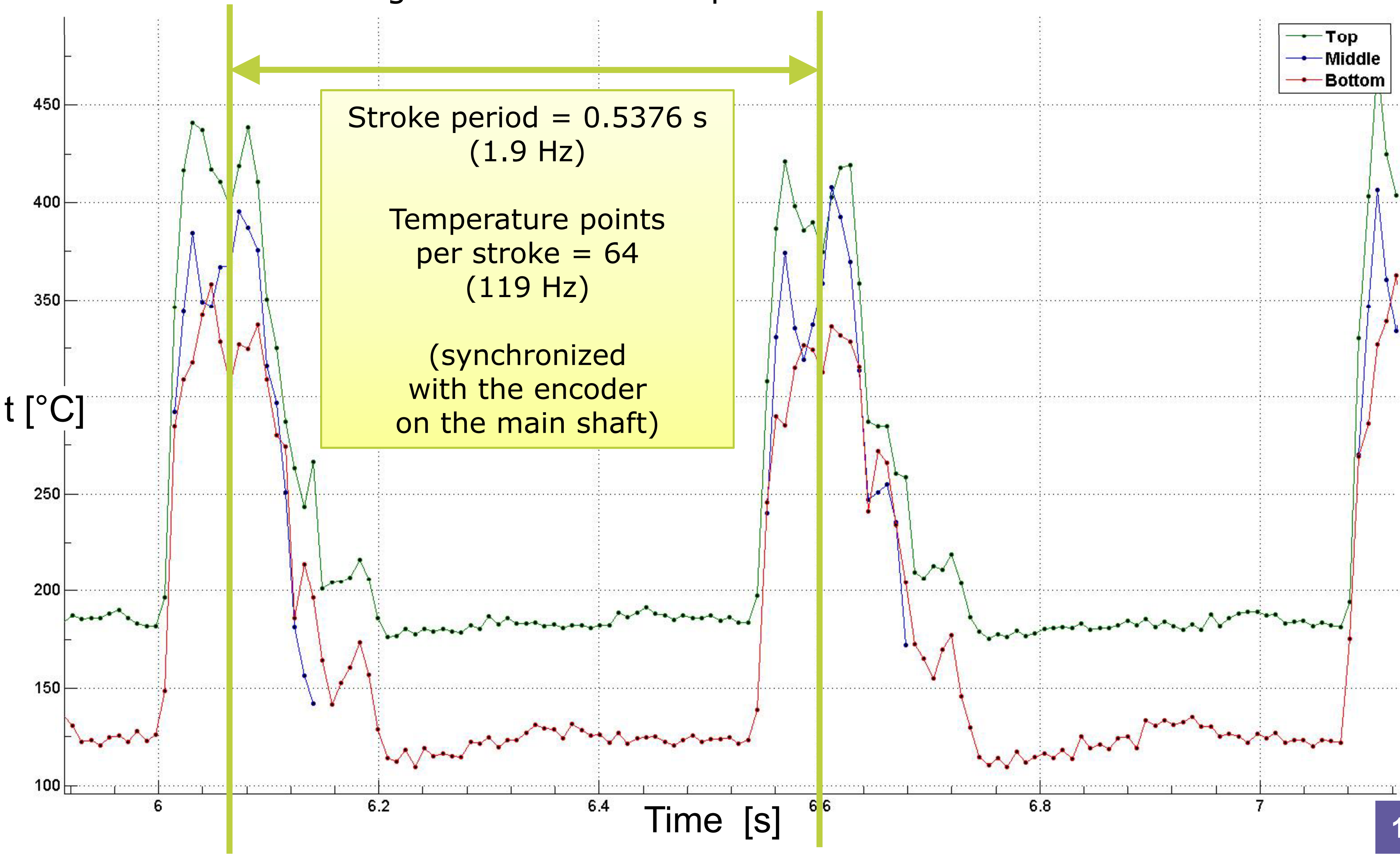
- **The system was successfully tested under real conditions**
- **The objective** was to measure gas temperature simultaneously in the three optical ports
  - measurements were synchronized with the encoder of the main shaft

MAN Diesel & Turbo
Copenhagen
R&D Department

Multichannel Spectrometer



- Gas temperature is not homogeneous
  - It is increasing from bottom to top



Gaseous Species Concentrations

- Calculations are based on **Line-By-Line** modeling of spectra*
  - which uses spectroscopic databases HITRAN, HITEMP, CDSD

Measured

•Gas temperature [K]	T_g
•Total pressure [atm]	p
•Absorption path length [cm]	L
•**Mole fraction of the species [%]**	c
•Instrument Line Shape Function	$ILS(v,v_c)$
•**Measured transmittance**	$\tau_m(v)$

Database parameters for the *i* th transition*

•Spectral line transition frequency [cm^{-1}]	v_0
•Air-broadened pressure shift [cm^{-1}/atm]	δ
•Air-broadened HWHM [cm^{-1}/atm]	γ_{air}
•Self-broadened HWHM [cm^{-1}/atm]	γ_{self}
•Coefficient of temperature dependence of γ_{air} and γ_{self}	n
•Spectral line intensity [cm^{-1}/(molecule cm^{-2})]	S_0
•Lower state energy of the transition [cm^{-1}]	E_0

Calculated*

•Pressure-shift correction of line position [cm^{-1}]	$v_0^*(p)$
•Temperature and pressure correction of line HWHM [cm^{-1}]	$\gamma(p,T_g)$
•Lorentz profile [1/cm^{-1}]	$f(v, T_g, p)$
•Temperature correction of line intensity [cm^{-1}/(molecule cm^{-2})]	$S(T_g)$
•Monochromatic absorption coefficient [1/(molecule cm^{-2})]	$k_i(v, T_g, p)$
•**Calculated transmittance**	$\tau_{clc}(v)$

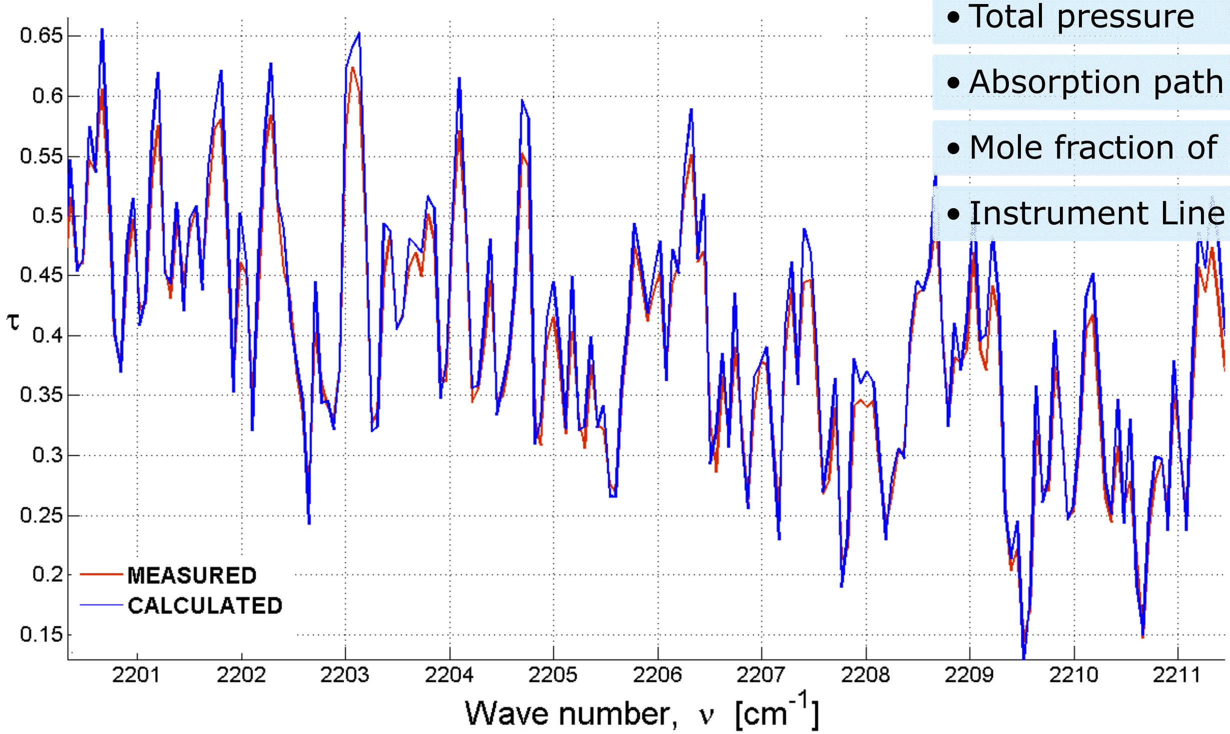
- The idea is to compare measured and calculated transmittances
- The mole fraction can then be obtained from the best match between the transmittances

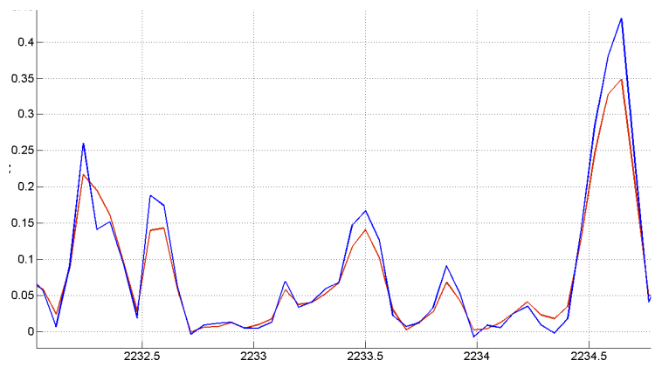
* **Rothman et al.** J. Quant. Spectrosc. Radiat. Transfer 60 (5) (1998) 665–710

Line-By-Line Modeling

- **CO_2 Transmittance**
  - **Measured** in a special hot gas cell developed at *Risø DTU*
  - **Vs**
  - **Calculated** using the HITEMP 2010 database

• Gas temperature	1000 K
• Total pressure	1 atm
• Absorption path length	53.3 cm
• Mole fraction of CO2	10 %
• Instrument Line Shape Function	*sinc*





Summary

- **Tomography methods**
  - Gas temperatures
    - Axisymmetric case
      - Parallel scanning
        - Successfully applied on a lab burner
      - Sweeping scanning
        - Considered theoretically

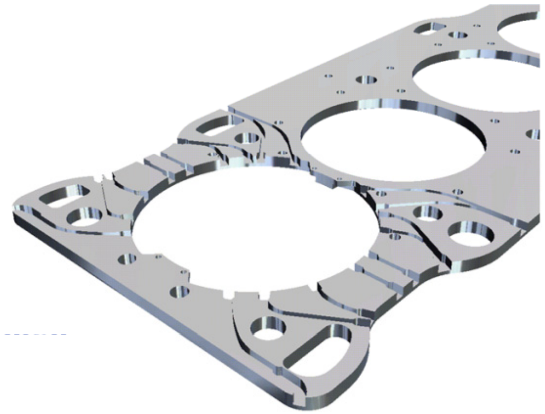
- **Tomography equipment**
  - Multichannel spectrometer
    - Optical fibres + Grating spectrometer + IR Camera
    - Successfully applied on a test marine engine
      - Simultaneous temperature measurements in the three optical ports of the exhaust duct

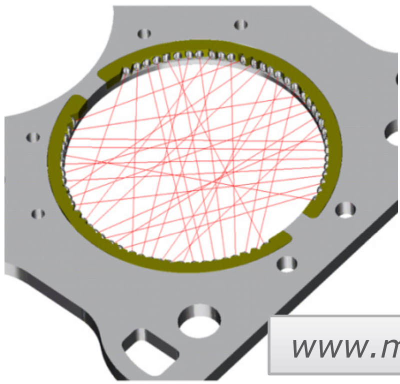
- **Concentration calculations**
    - Measurements in the special gas cell are compared with the line-by-line modeling results
      - Excellent agreement in a wide spectral range

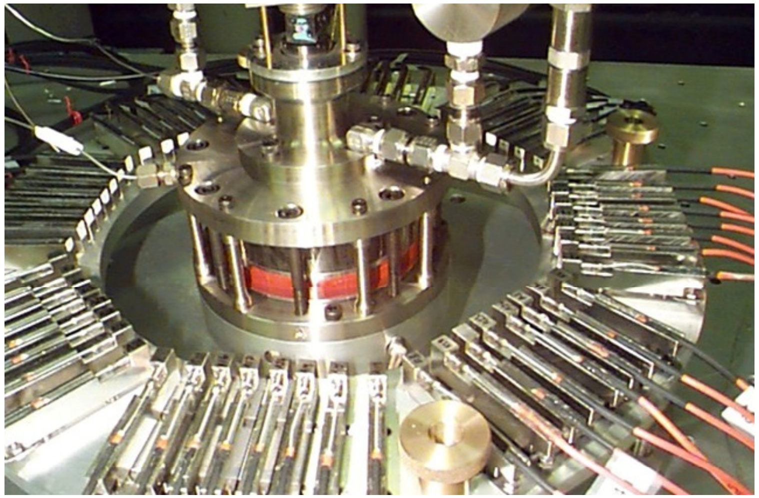
Thank you for your attention!

Tomography in Engines

- **An existing technique**
- A group at the University of Manchester headed by Hugh McCann
  - have established the technique of high-speed Chemical Species Tomography, using near-IR absorption spectroscopy
  - The concentration distribution of a target molecule can be imaged at rates up to 4,000 frames per second

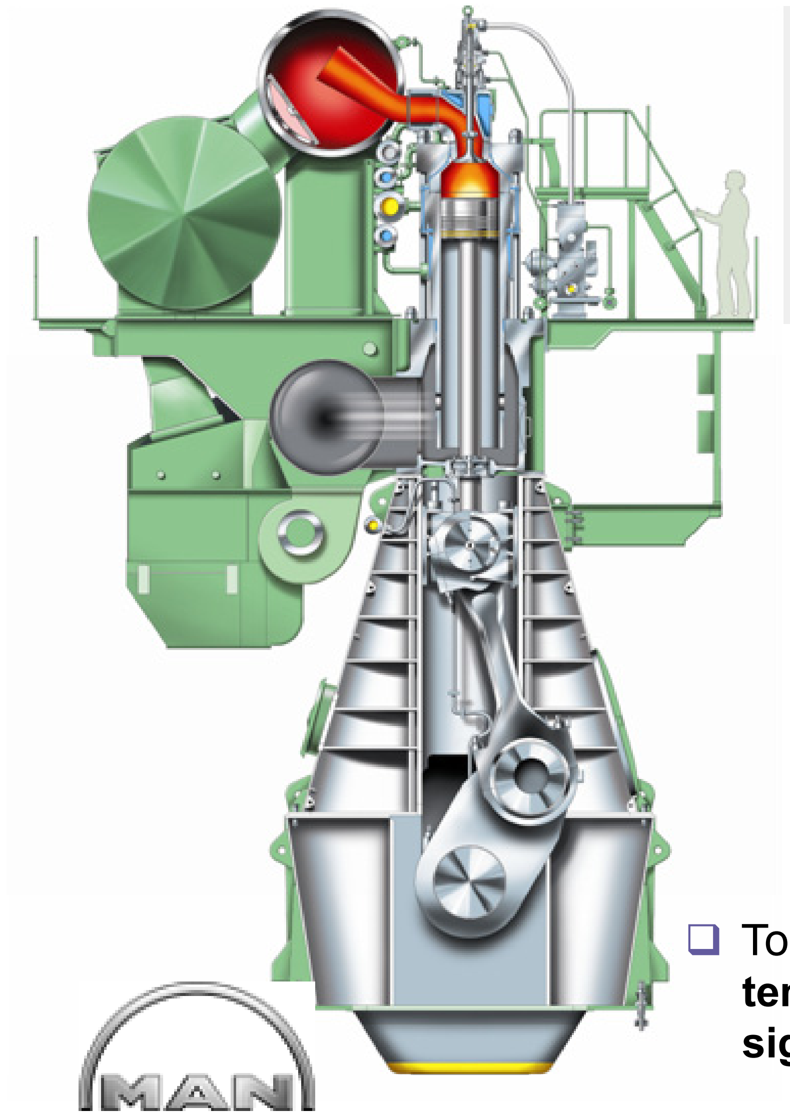






www.manchester.ac.uk/research/H.mccann/research

The Aim of the Work



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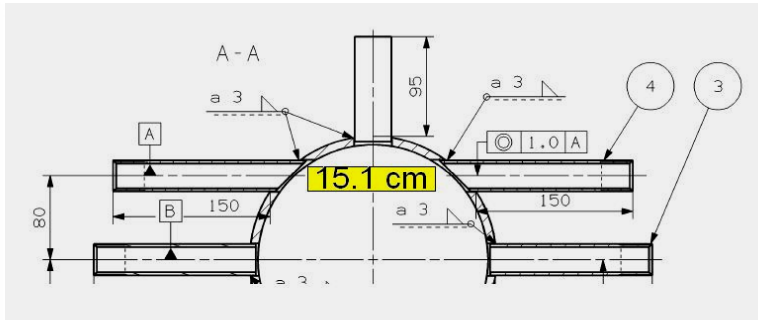
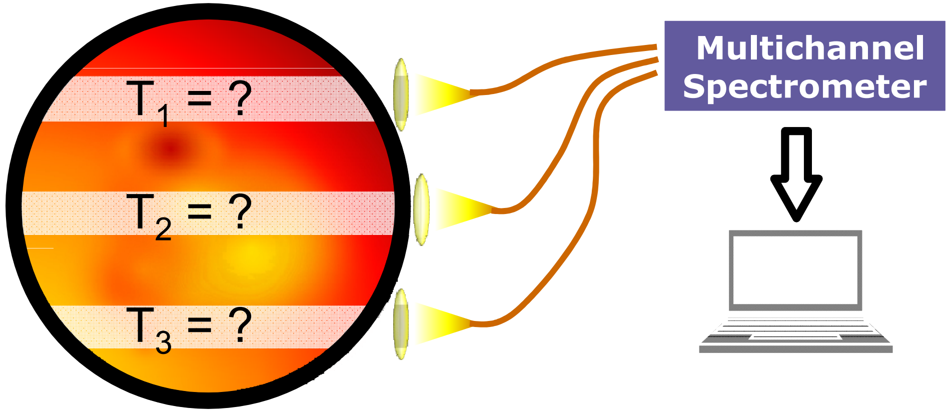
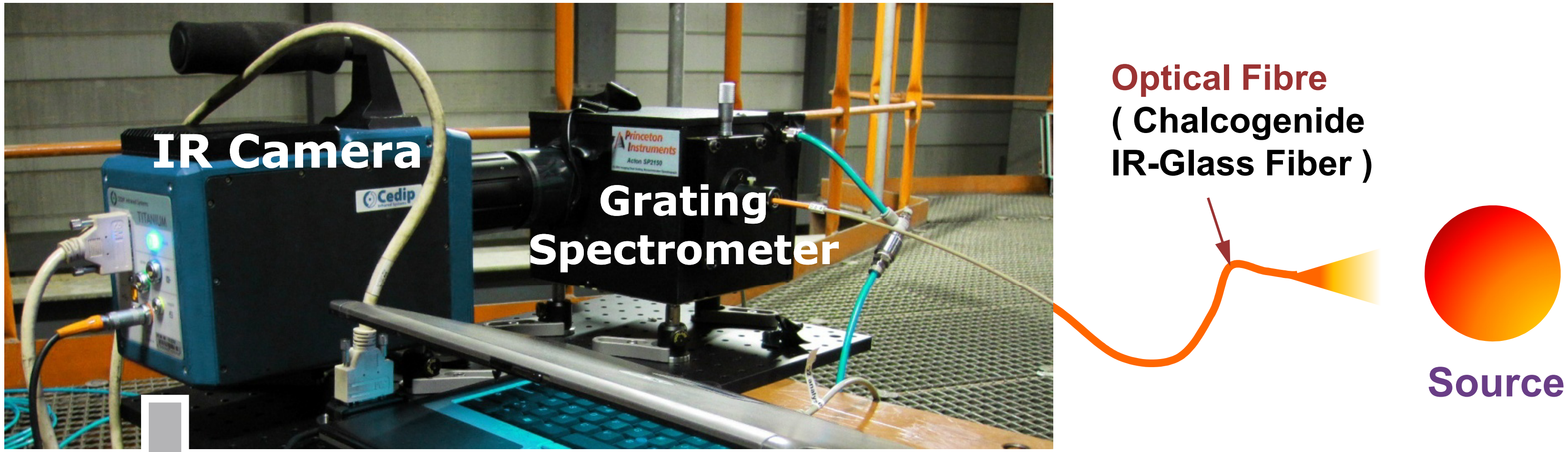


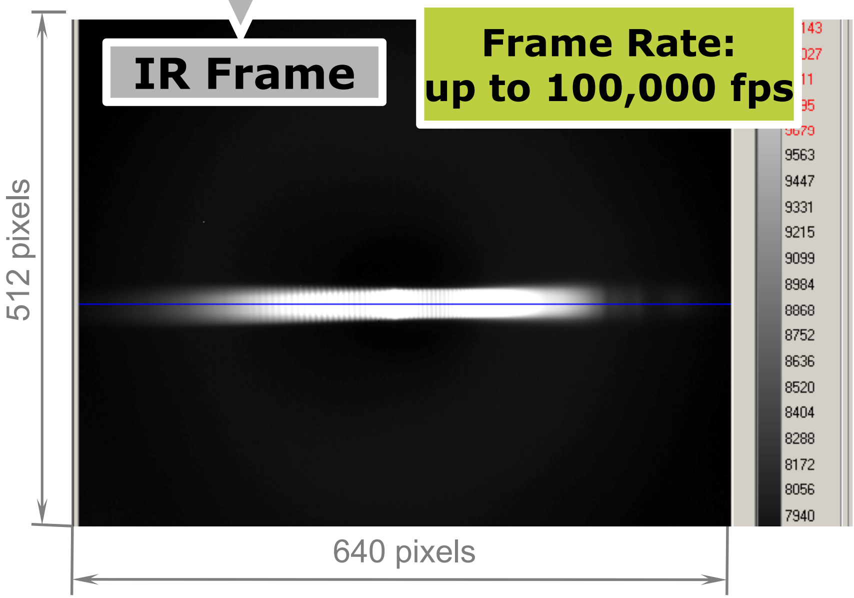
The exhaust duct of a cylinder
(cross-section)



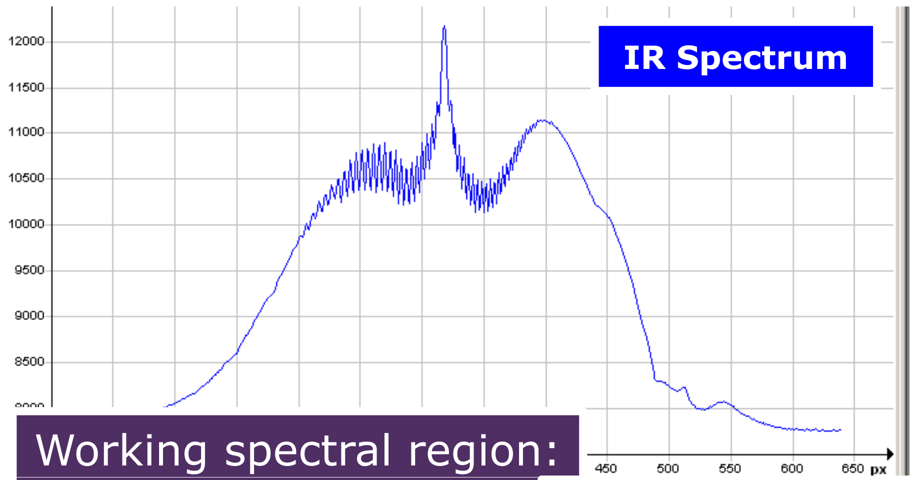
- To develop a system for **simultaneous gas temperature measurements from several lines of sight**
- To apply the system on an exhaust duct of a large marine Diesel engine

The System with One Channel





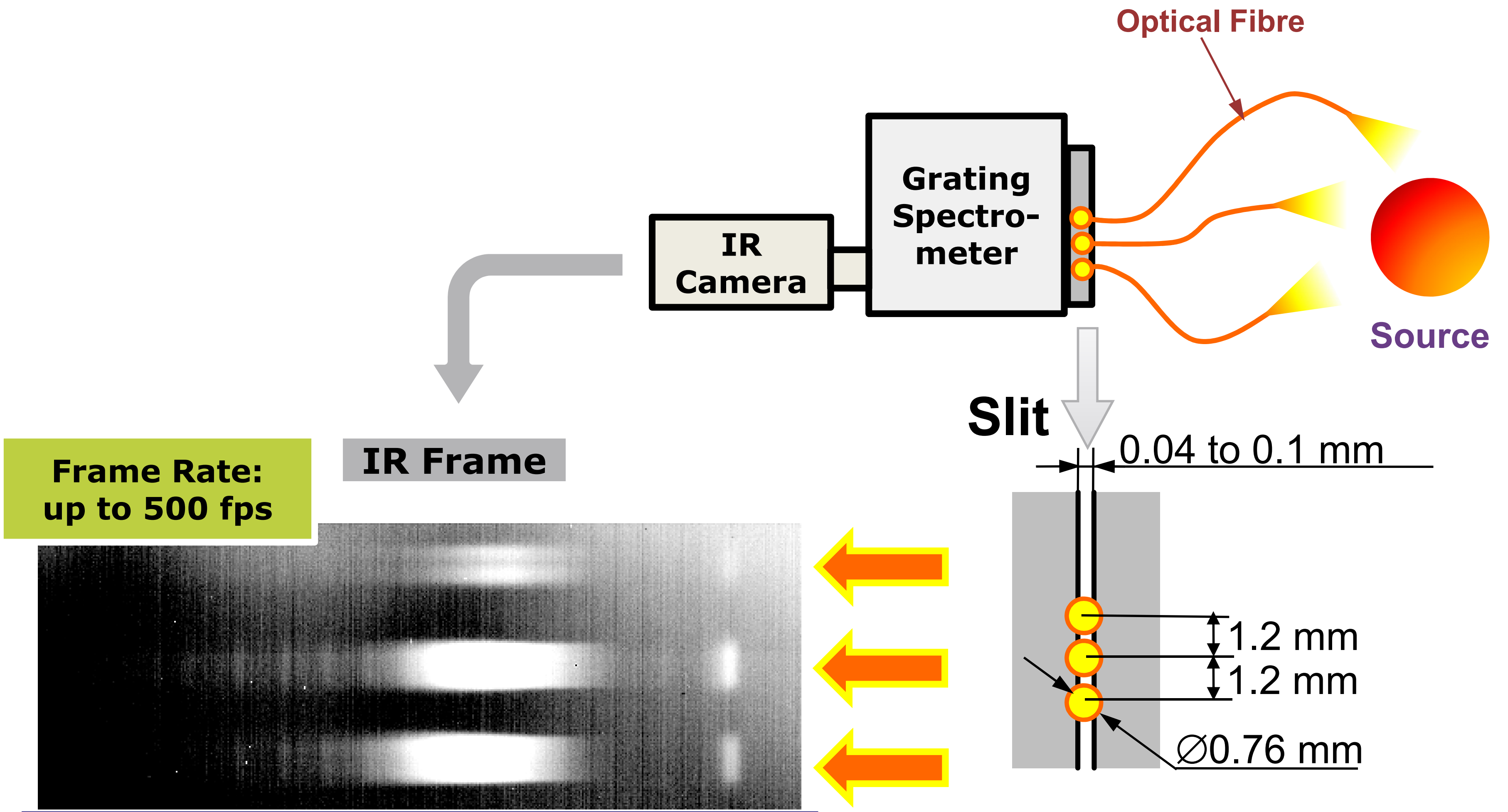
Frame Rate:
up to 100,000 fps



Working spectral region:
3.8–5 μm
(2000–2600 cm^{-1})

Resolving power:
6 nm
(4 cm^{-1})

The System with Three Channels

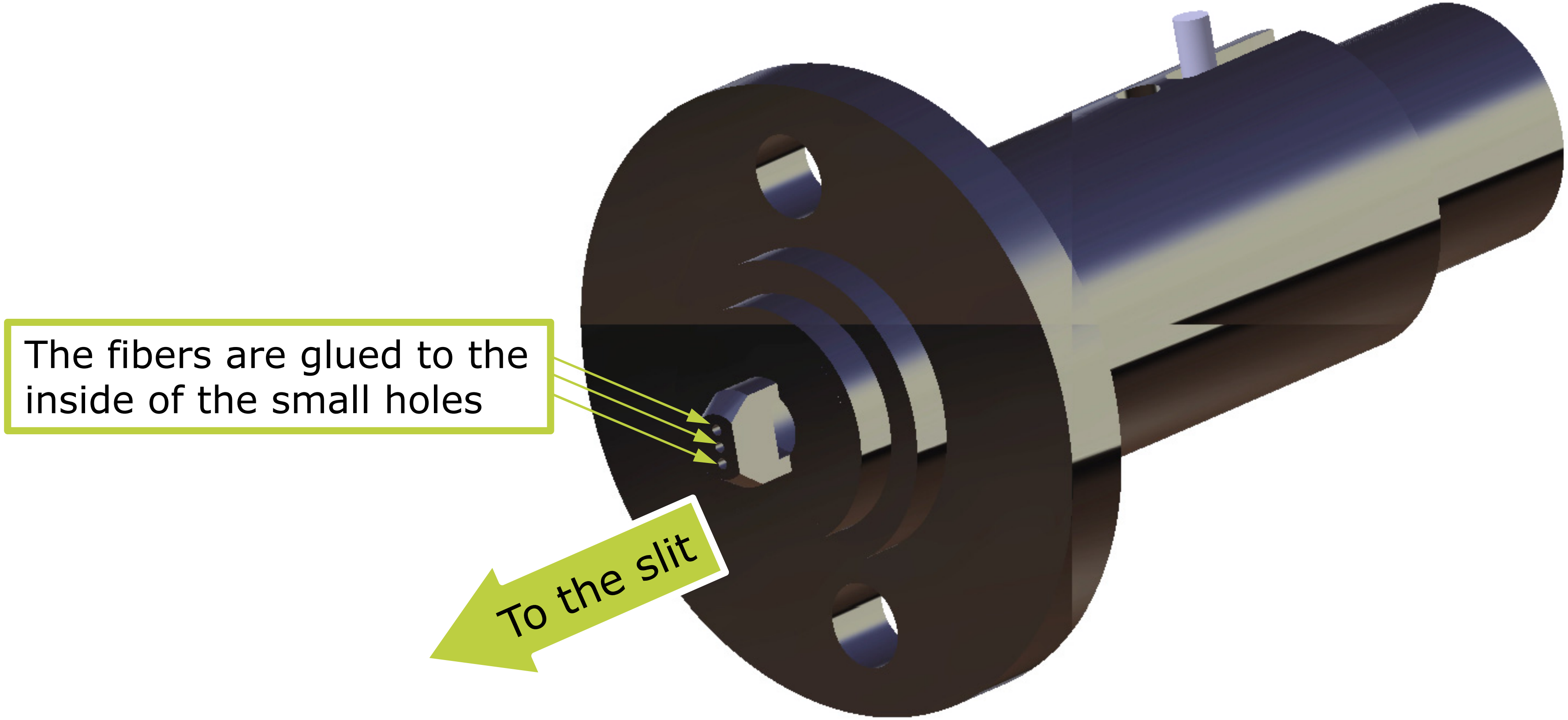


Simultaneous spectral measurements

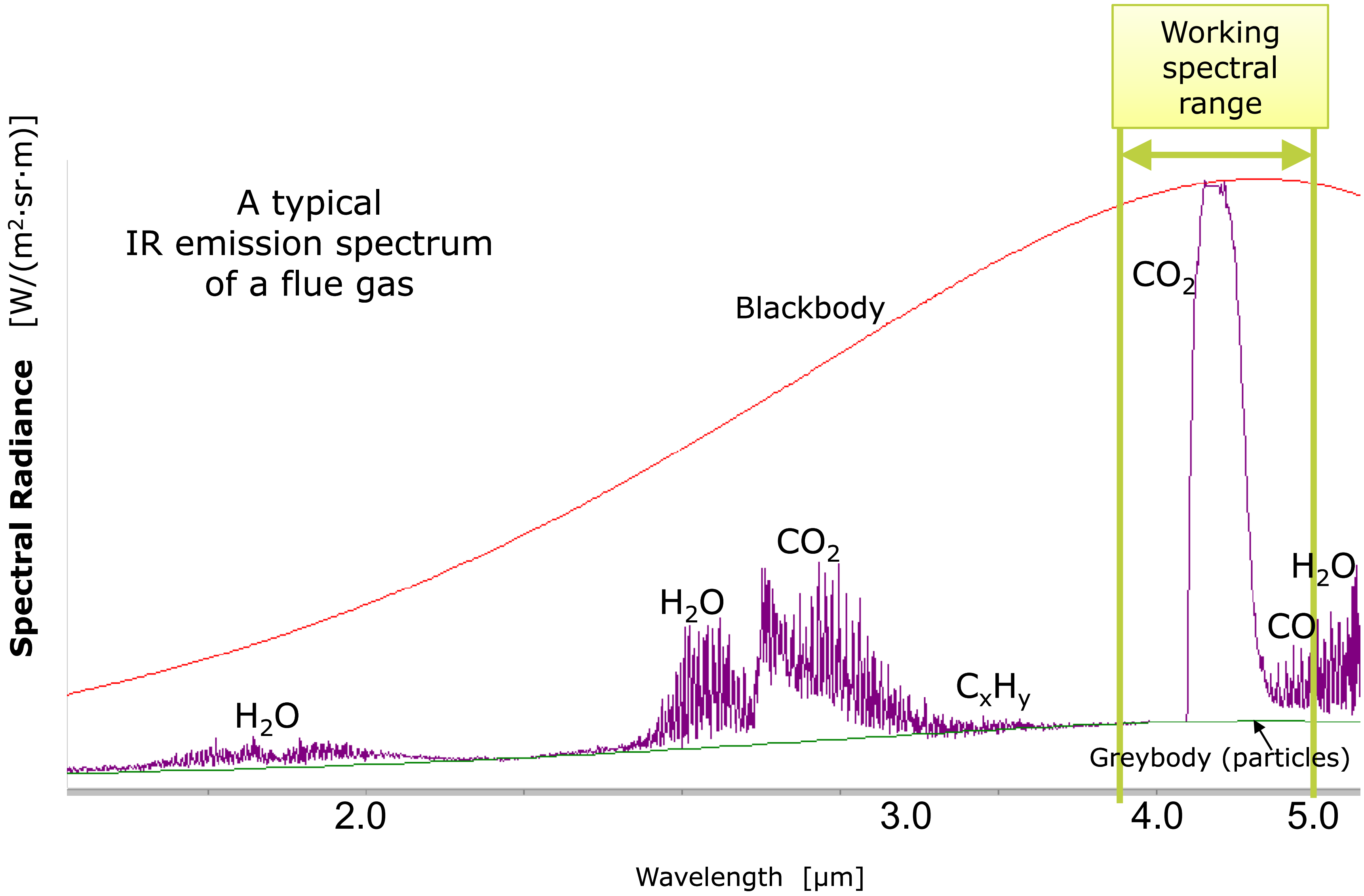
Three is not a limit!

Design Details

- A special mechanical adaptor
  for coupling the three fibers together



IR Emission Spectrum



Temperature Measurement Method

I_λ^0 → **Gas sample at T [K]** → $I_\lambda(T)$

- **Spectral absorptivity**:
  - is the portion of incident energy absorbed at wavelength λ

$$\alpha_\lambda(T) = \frac{I_\lambda^0 - I_\lambda(T)}{I_\lambda^0}$$

- The sample also emits radiation:

Gas sample at T [K] → $N_\lambda(T)$

  - $\boldsymbol{N_\lambda(T)}$ **– spectral radiance** [W/(m²·sr·m)]

- Kirchhoff's law:

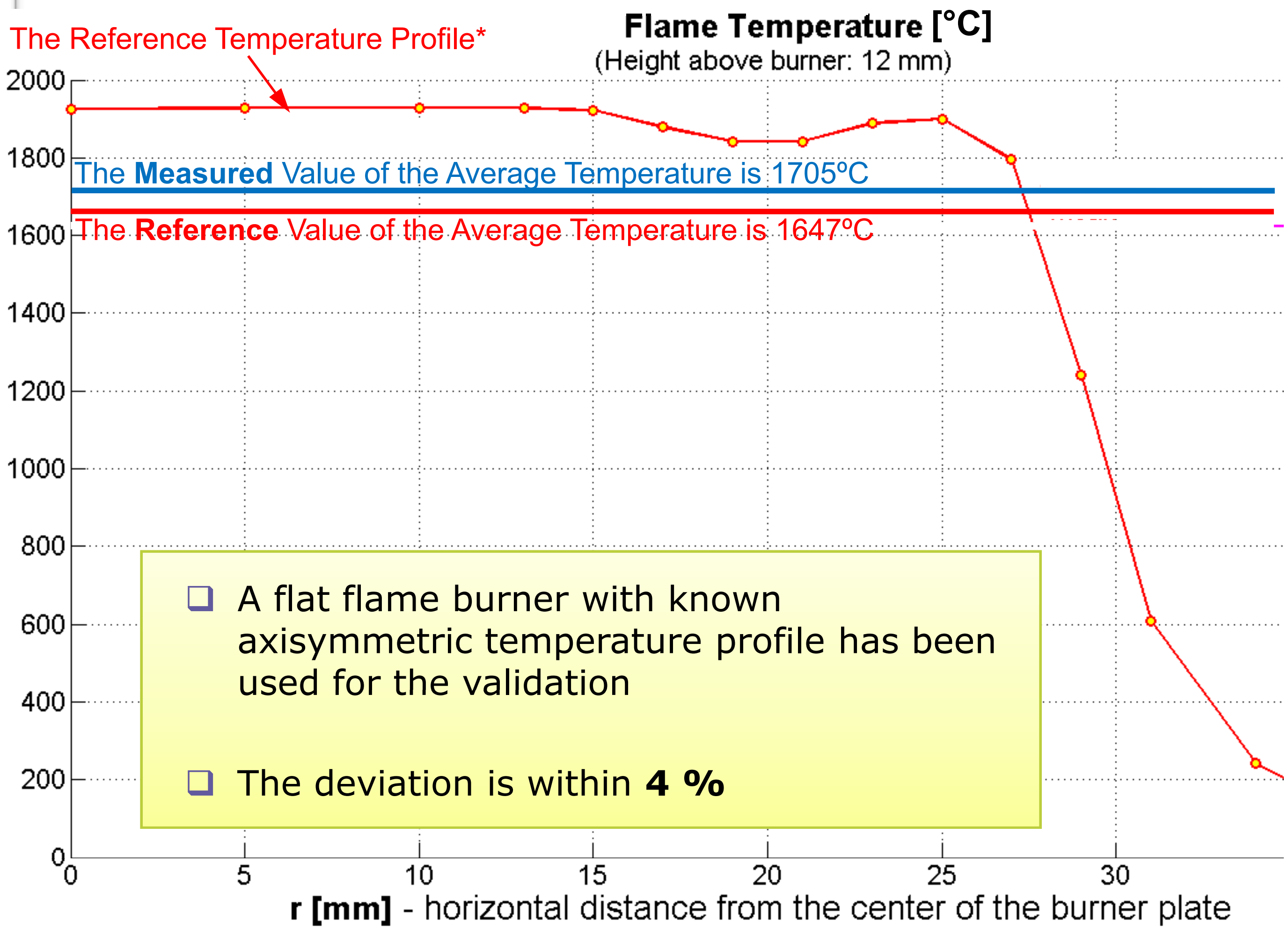
$$\frac{N_\lambda(T)}{\alpha_\lambda(T)} = N_\lambda^b(T)$$

is a universal function of λ and T
ndent of a particular sample
nction on the right-hand side is given by:

$$N_\lambda^b(T) = \frac{C_1}{\pi\lambda^5\left(e^{C_2/\lambda T} - 1\right)}$$

R.H.Tourin, "Spectroscopic Gas Temperature Measurement", *Elsevier Publishing Company* (1966)

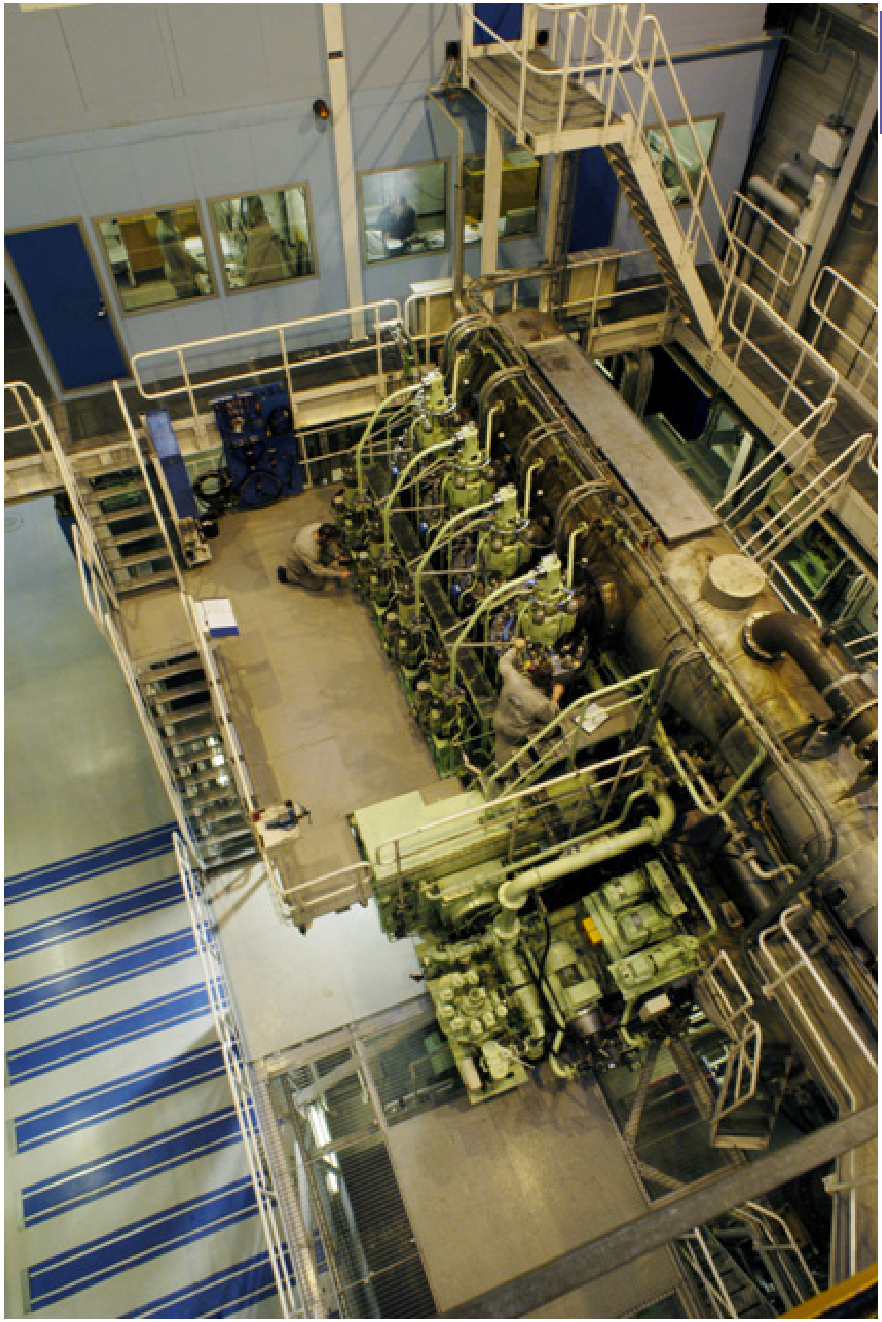
Validation

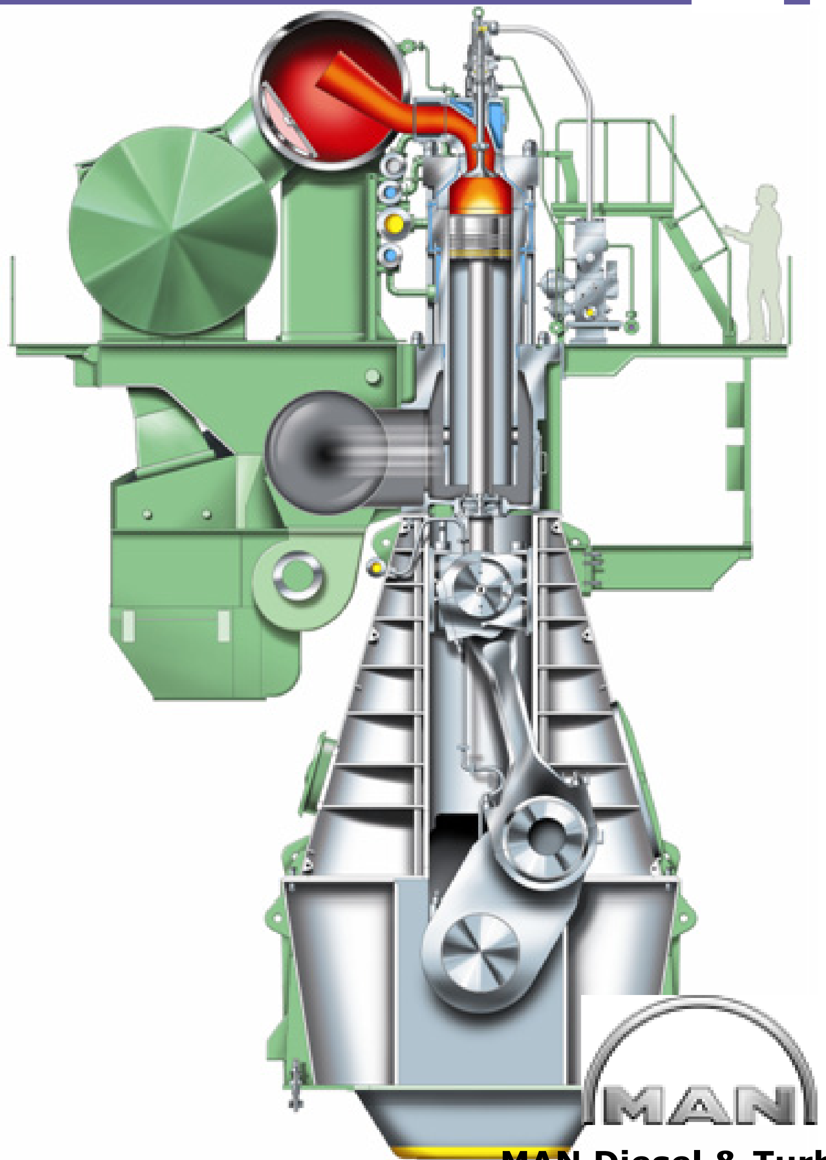


- A flat flame burner with known axisymmetric temperature profile has been used for the validation
- The deviation is within **4 %**

***Hartung et al.** Meas. Sci. Technol. 17 (2006) 2485–2493

The Marine Diesel Engine





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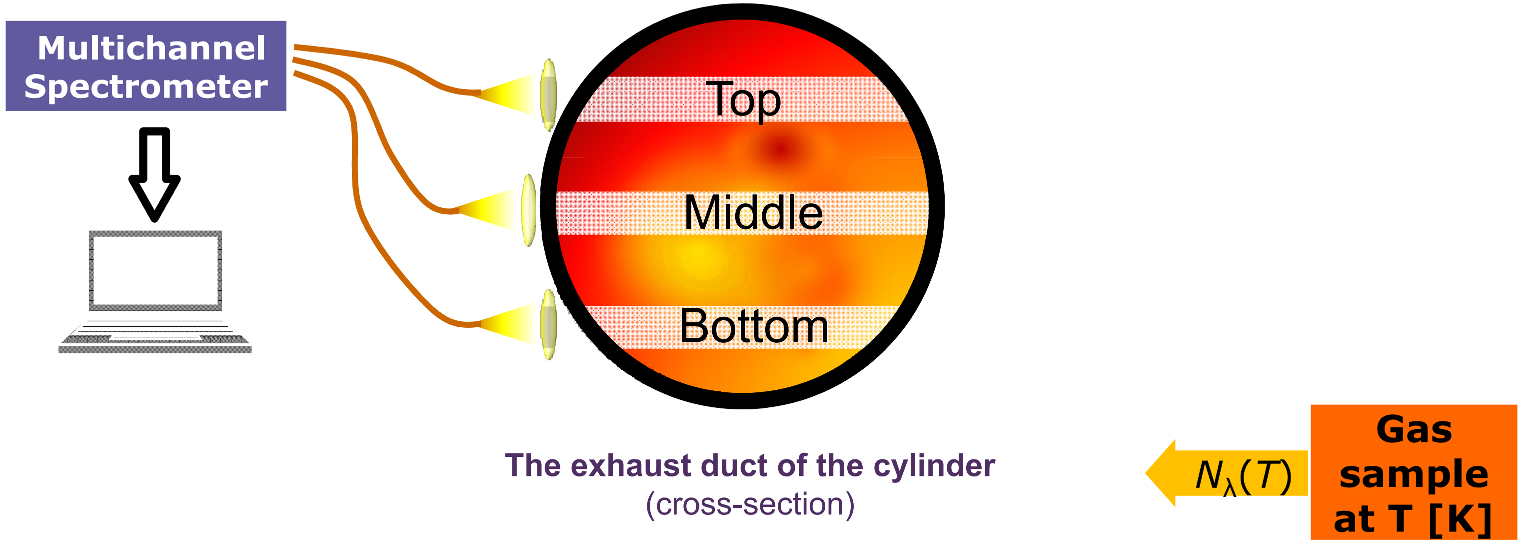
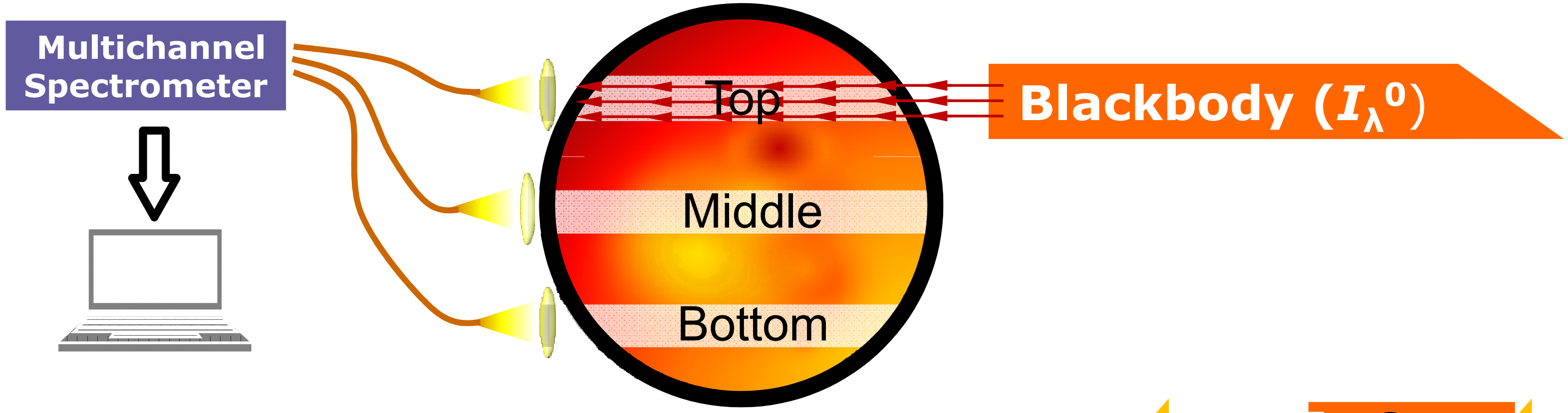
The Measurement Diagram



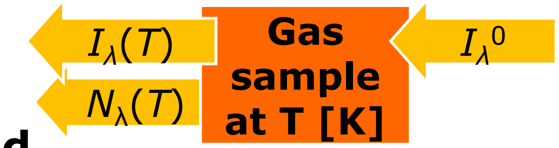
The exhaust duct of the cylinder
(cross-section)

- **Simultaneous emission measurements**
- They give spectral radiances $\boldsymbol{N_\lambda^{Top}}$, $\boldsymbol{N_\lambda^{Middle}}$, $\boldsymbol{N_\lambda^{Bottom}}$ as functions of time for the top, middle and bottom ports

The Measurement Diagram



The exhaust duct of the cylinder
(cross-section)



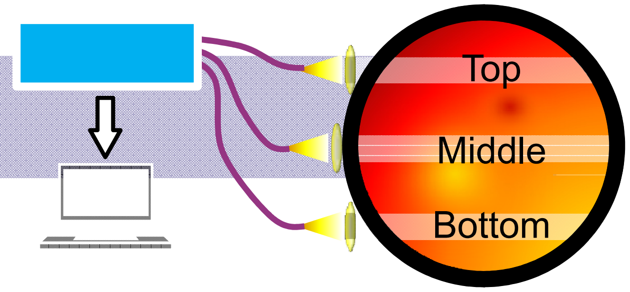
- **Transmission measurements were performed for one port at a time**

- They are necessary for the calculation of spectral absorptivities $\boldsymbol{\alpha_\lambda^{Top}}$, $\boldsymbol{\alpha_\lambda^{Middle}}$ and $\boldsymbol{\alpha_\lambda^{Bottom}}$

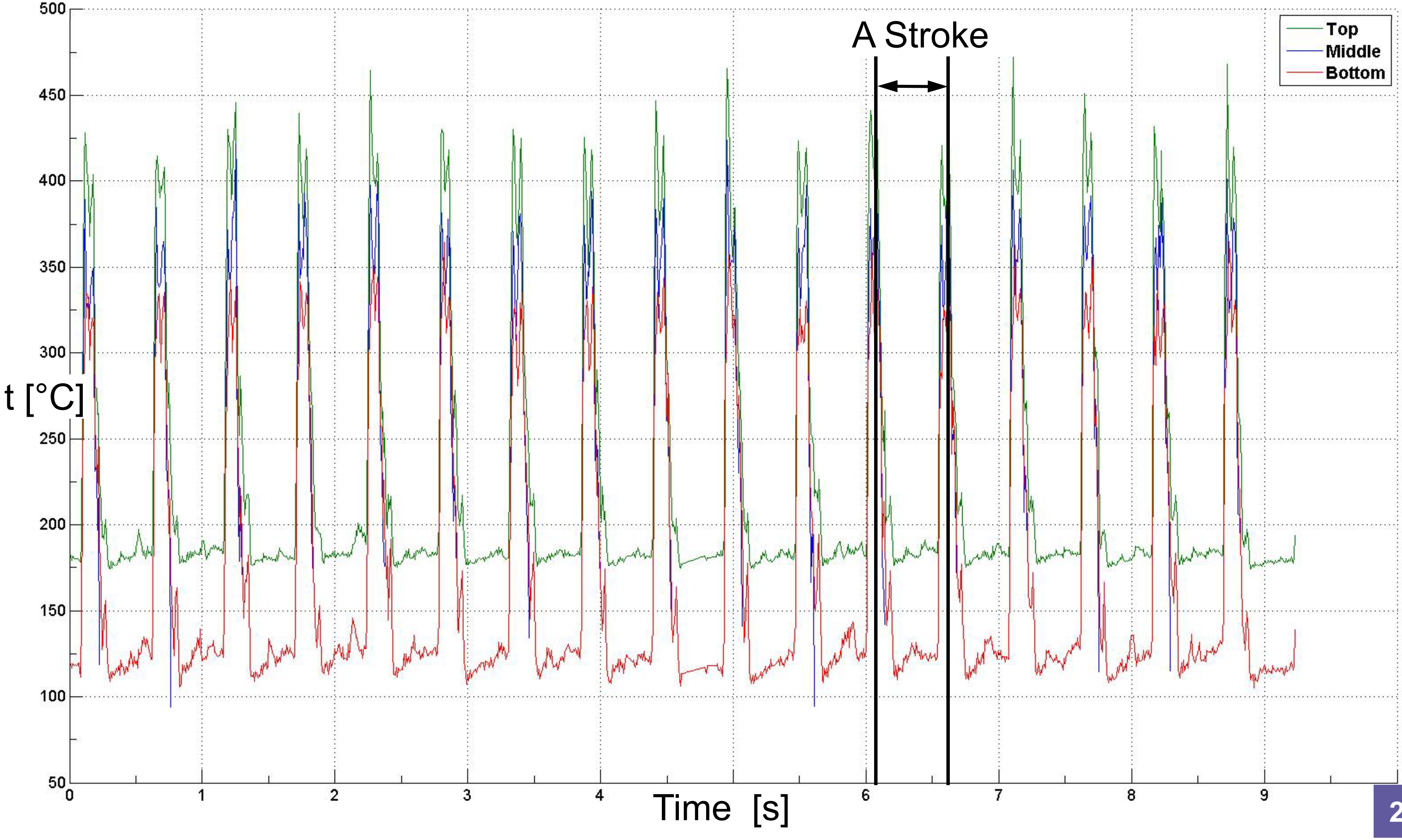
- The ananlysis has shown that $\boldsymbol{\alpha_\lambda}$ for all the three ports can be assumed to be 0.9

- The temperatures for each port as functions of time can now be obtained from the spectral radiances $\boldsymbol{N_\lambda^{Top}}$, $\boldsymbol{N_\lambda^{Middle}}$, $\boldsymbol{N_\lambda^{Bottom}}$ and $\boldsymbol{\alpha_\lambda}$=0.9 using Kirchhoff's law and the Planck function.

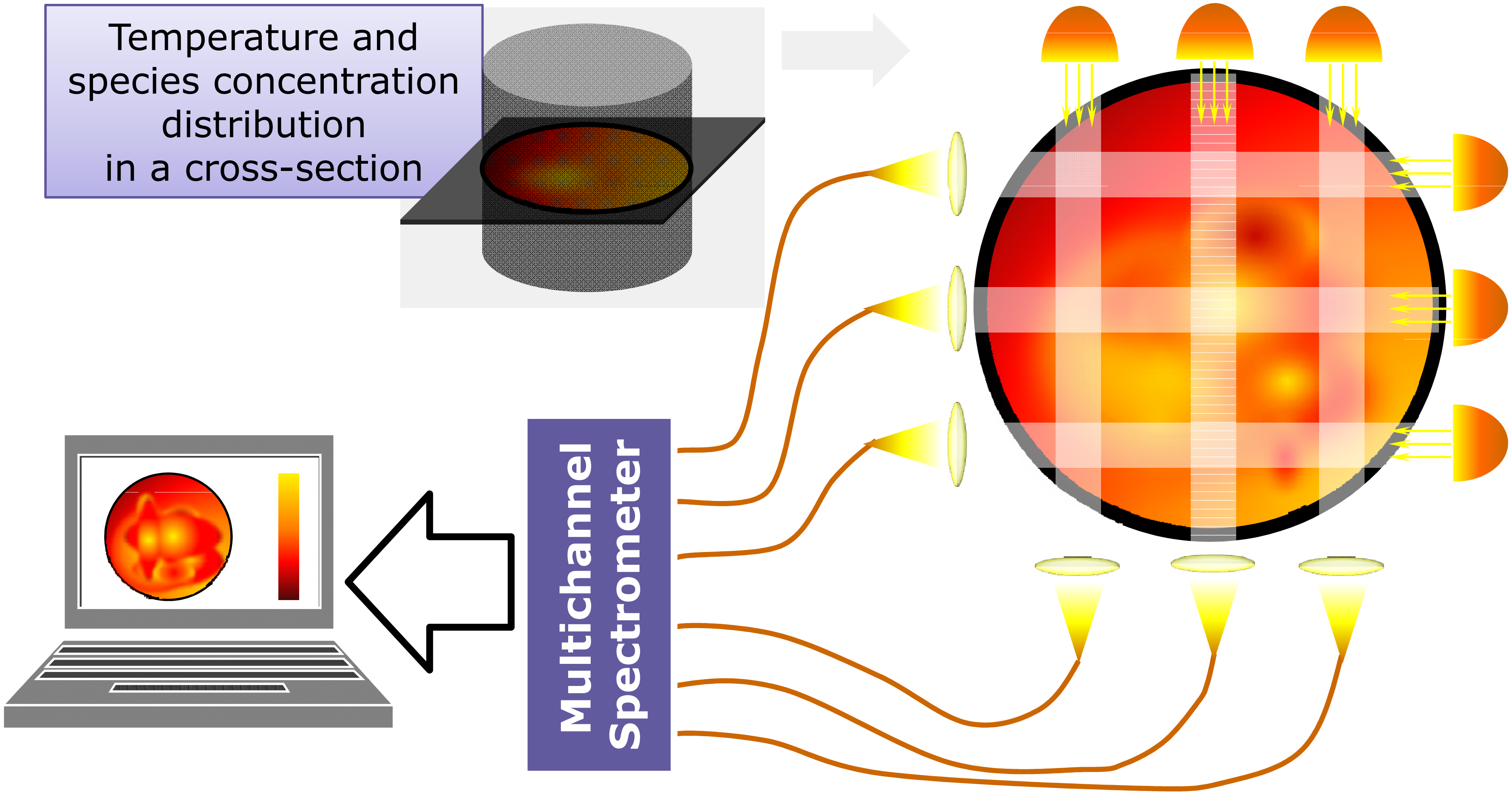
Gas Temperature vs Time



- Temporal resolution 119 Hz (64 points per stroke)



Towards the tomography of hot gases



Conclusions

- The three-channel system has been
  - developed
  - validated
  - applied on a large scale

- The results of the application on the marine Diesel engine:
  - Temperatures as functions of time have been obtained for the three ports on the exhaust duct

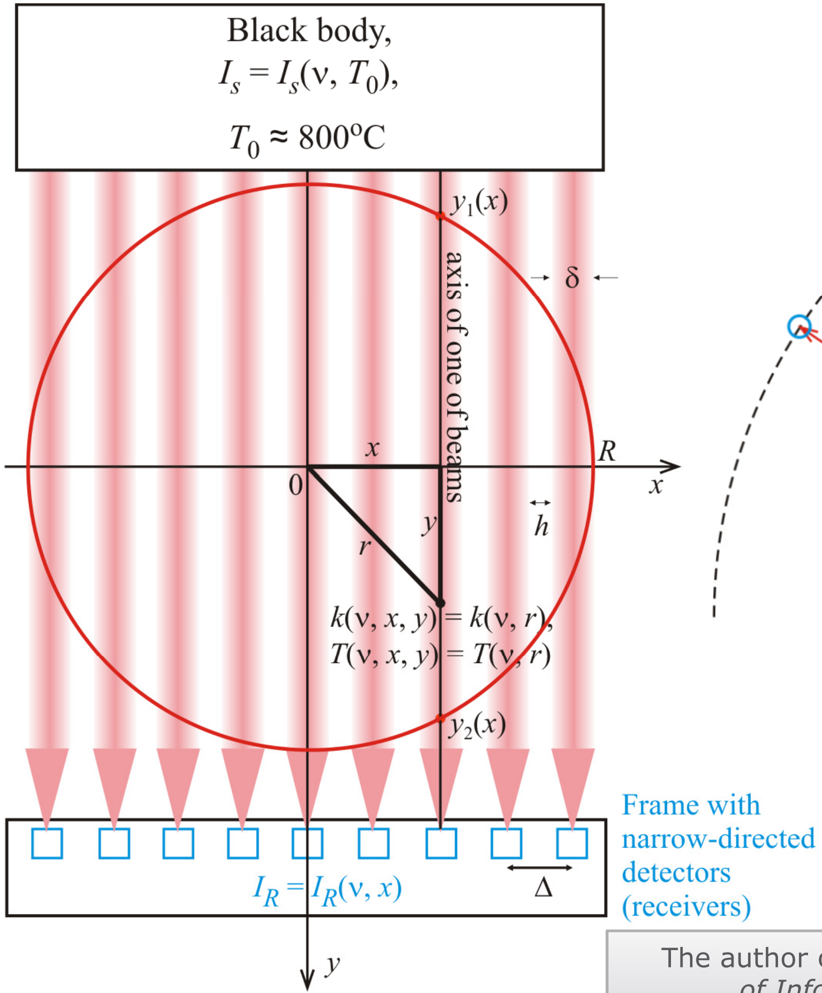
- The three fibers is not a limit

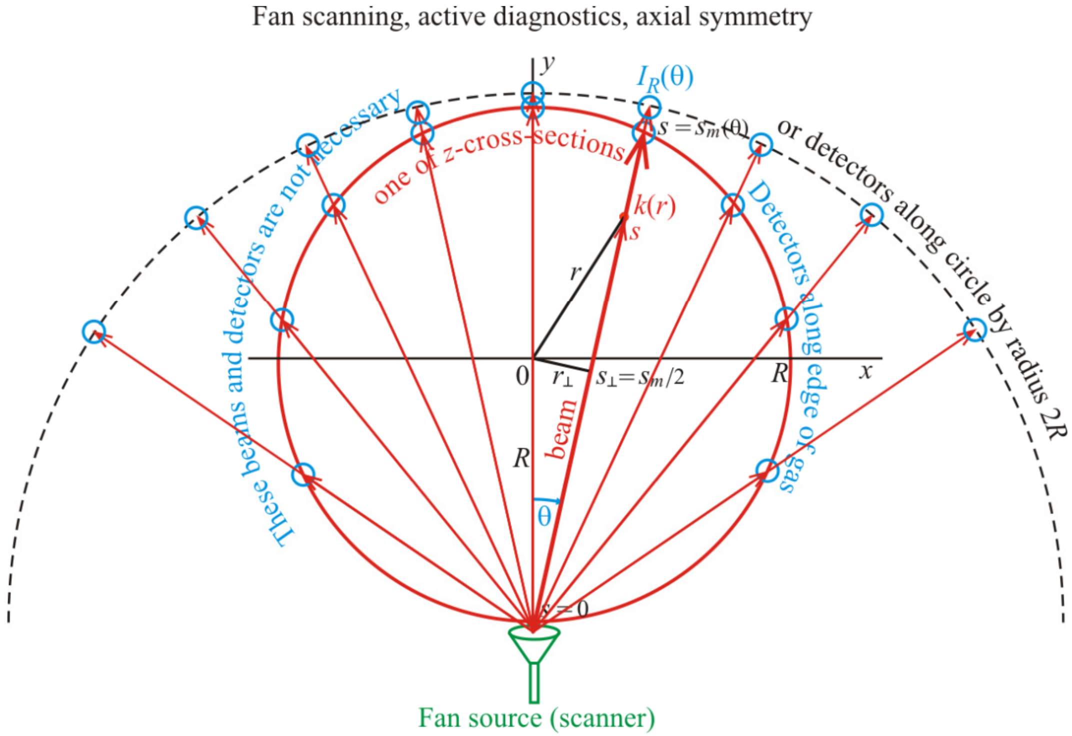
- The system is flexible

- The system can find many other applications

Towards the tomography of hot gases

- The 1st step is to validate the methods using the above mentioned lab burner with the known **axisymmetric** temperature profile
- The two measurement diagrams are currently under investigation





The radiative transfer equation:

$$dI_\nu(x,y) = -k_\nu(x,y)\left[I_\nu(x,y) - I_\nu^{Planck}(T_g(x,y))\right]dy$$

The author of the diagrams on this slide: **V. Sizikov**, *National Research Unive... of Information Technologies, Mechanics and Optics, Saint Petersburg, R...*

Parallel Scanning

Scheme 1. Previous equation is written in the form of Abel's singular integral equation:

$$2\int_x^R \frac{r}{\sqrt{r^2-x^2}}k(r)dr = q(x), \quad 0 \le x \le R,$$

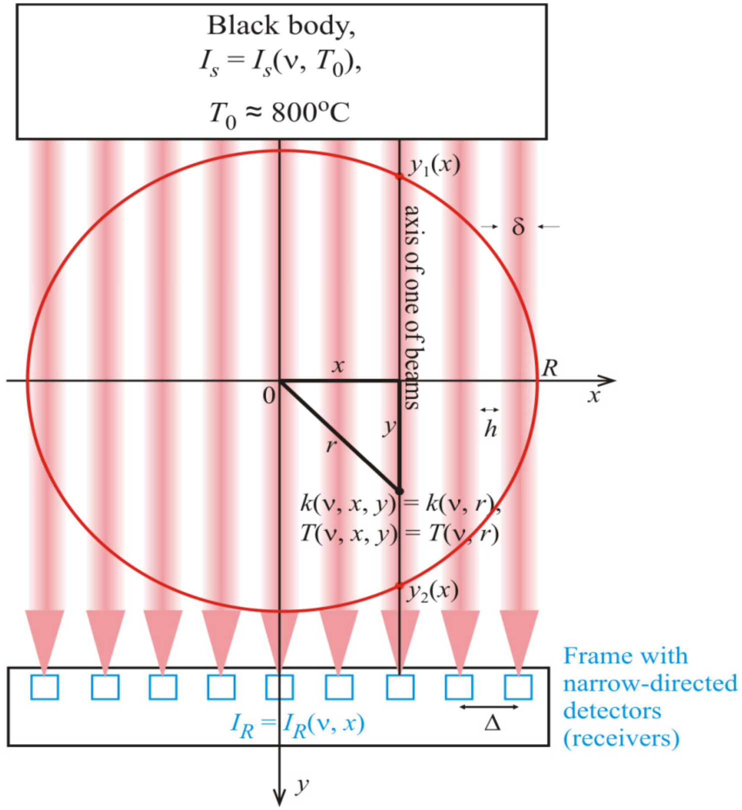
$$q(x) = -\ln\left\{\frac{I_R(x)}{I_s(T_0)} - \right.$$

$$-\int_x^R \frac{r}{\sqrt{r^2-x^2}}k(r)\frac{I_s(T_g(r))}{I_s(T_0)}\left[\exp\left(\int_x^r \frac{r'}{\sqrt{r'^2-x^2}}k(r')dr'\right)+\right.$$

$$\left.\left.+\exp\left(-\int_x^r \frac{r'}{\sqrt{r'^2-x^2}}k(r')dr'\right)\right]dr \cdot \exp\left(-\int_x^R \frac{r}{\sqrt{r^2-x^2}}k(r)dr\right)\right\},$$

which is solved by iterations with respect to $k(r)$. In each iteration, after finding $k(r)$, one can find $T_g(r)$ using the spectroscopic databases.

Scheme 2 – of type Scheme 1, but for $T_g >> T_0$ and flame emission is stronger than absorption.



Scheme 3. Suppose that $k(r)$ has been taken from a database. Then $J(r) = I_s(T_g(r))/I_s(T_0)$ can be found by solving a singular integral equation of Abel's type, and temperature profile will be equal

$$T_g(r) = (hc\nu/k_B)\Big/\ln\left(\frac{\exp(hc\nu/k_B T_0)-1}{J(r)}+1\right).$$

Parallel Scanning

- The **radiative transfer equation** is a **differential equation** with respect to $I(x,y)$ for given $k(T_g) = k(T_g(x,y))$.

- The more important is the following **integral equation** with respect to $k(T_g(x,y))$ from measured $I_R(x)/I_s(T_0)$:

$$\frac{I_R(x)}{I_s(T_0)} = \exp\left(-\int_{y_1(x)}^{y_2(x)} k(T_g(x,y))\,dy\right) + \\ + \left\{\int_{y_1(x)}^{y_2(x)} k(T_g(x,y))\frac{I_{Planck}(T_g(x,y))}{I_s(T_0)}\exp\left(\int_{y_1(x)}^{y} k(T_g(x,y'))\,dy'\right)dy\right\}\times \\ \times\exp\left(-\int_{y_1(x)}^{y_2(x)} k(T_g(x,y))\,dy\right).$$

- There are two unknown functions k and T_g. So we consider axial symmetry: $T_g = T_g(r)$, $k = k(T_g(r))$ and obtain Abel's singular integral equation.
- Moreover, we consider **three cases**:

Case 1. Previous equation is written in the form of Abel's singular integral equation:

$$2\int_x^R \frac{r}{\sqrt{r^2-x^2}} k(r)\,dr = q(x), \quad 0 \le x \le R,$$

$$q(x) = -\ln\left\{ \frac{I_R(x)}{I_s(T_0)} - \right.$$

$$-\int_x^R \frac{r}{\sqrt{r^2-x^2}} k(r) \frac{I_s(T_g(r))}{I_s(T_0)} \left[\exp\left(\int_x^r \frac{r'}{\sqrt{r'^2-x^2}} k(r')\,dr' \right) + \right.$$

$$\left. \left. + \exp\left(-\int_x^r \frac{r'}{\sqrt{r'^2-x^2}} k(r')\,dr' \right) \right] dr \cdot \exp\left(-\int_x^R \frac{r}{\sqrt{r^2-x^2}} k(r)\,dr \right) \right\},$$

which is solved by iterations with respect to $k(r)$. In each iteration, after finding $k(r)$, one can find $T_g(r)$ using the spectroscopic databases.

Case 2 the same as case 1, but for $T_g >> T_0$ which means that flame emission is stronger than absorption.

Case 3. Suppose that $k(r)$ has been taken from a database. Then $J(r) = I_s(T_g(r))/I_s(T_0)$ can be found by solving a singular integral equation of Abel's type, and the temperature profile will then be equal to

$$T_g(r) = (hc\nu/k_B) \Big/ \ln\left(\frac{\exp(hc\nu/k_B T_0) - 1}{J(r)} + 1 \right).$$